5

Trends and Outlook in High-Temperature Fuel Cells for Clean Coal Technology

TAKAO WATANABE
Affiliated Fellow
SEIJI MAEDA
Environment and Energy Research Unit

1 Introduction

Coal is a vital energy source that accounts for about 20% of the primary energy supply of Japan. However, from the perspective of reducing global warming problem, coal has a high environmental impact due to its high CO_2 emission intensity and impurity contents such as sulfur, compared to other fossil fuels. Environmentally harmonious coal technology (clean coal technology) is featured as a technology to overcome the drawbacks of coal in the 2004 November issue of Science & Technology Trends.

As primary energy demand increases sharply with the rapid economic development in China and other Asian countries, coal is increasingly vital for energy security since it is abundant worldwide and is not concentrated in particular regions. Despite the recent crude oil price hikes, coal prices have been stable at low levels (Figure 1)[1]. The consumption of coal as a primary energy source to cover the rapidly increasing electricity demand with the expanding economy mainly in Asian countries is likely to further increase (Figure 2)[2].

As global warming events such as extreme weather are becoming serious, clean coal technology is increasingly important for allowing both the use and environmental harmony of coal[3]. In particular, since the Intergovernmental Panel on Climate Change (IPCC) concluded in September 2005 that CO_2 capture and storage (CCS) technology for power plants plays a major role in combating climate change[4], there have been active efforts, mainly in foreign countries, to achieve clean coal technology as the ultimate power generation technology with near-zero emissions, including CO_2 capture, collection and storage.

Of clean coal technologies, the integrated coal gasification fuel cell combined cycle (IGFC) is

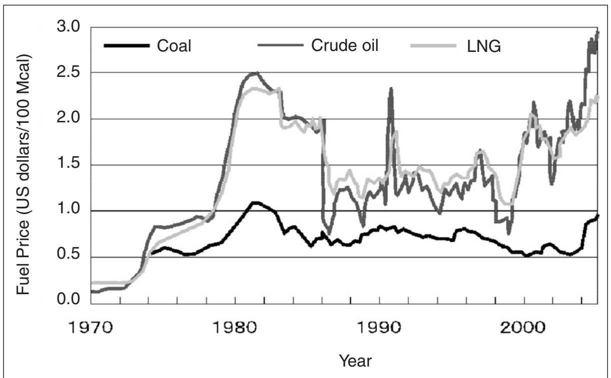


Figure 1 : Trend in imported fuel price in Japan

Prepared by the STFC based on Reference[1]

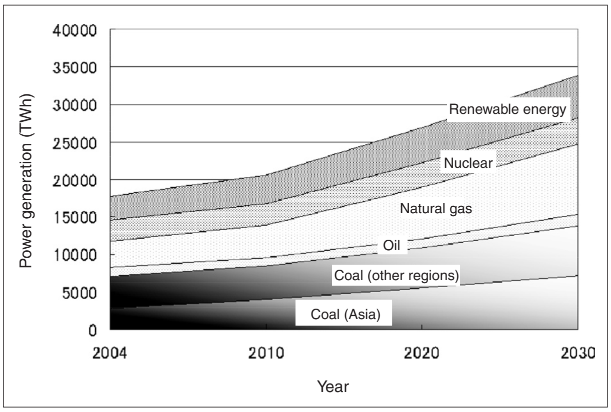


Figure 2 : Actual and forecast power generation of the world

Prepared by the STFC based on Reference[2] the most efficient power generation system with a low environmental impact and is expected to become the "ultimate coal-based power generation technology." High-temperature fuel cells are used for the power-generation portion of IGFC. The research and development of high-temperature fuel cell technology has been actively pursued in Japan.

This report provides an overview of IGFC technology and describes trends in research and development of the key technology of high-temperature fuel cells. It then identifies issues in promoting research and development of high-temperature fuel cells in Japan, and proposes policy measures to be taken, based on a comparison with overseas trends.

2 Overview of clean coal technology focused on the integrated coal gasification fuel cell combined cycle (IGFC)

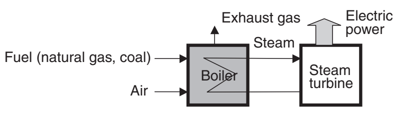
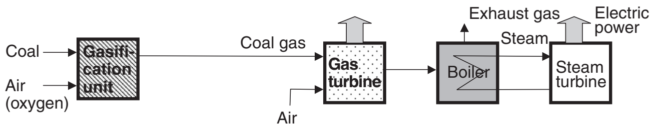
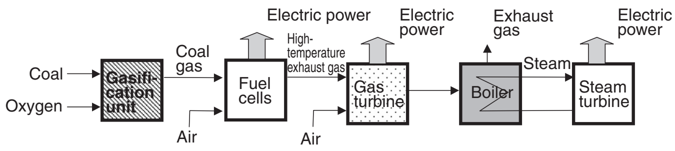
The integrated coal gasification combined cycle (IGCC) is described in detail in the 2004 November issue of Science & Technology Trends as a clean coal technology contributing to high-efficiency power generation. IGCC is a combined power generation system in which gas turbines are driven by combustion energy from burning gasified-coal fuel (coal gas), instead of directly burning coal, and steam turbines are driven by exhaust heat. This system allows high-efficiency power generation by combining steam and gas turbines and using energy in a cascading manner. In Japan, a demonstration IGCC plant with a capacity about half that of commercial power plants is under construction, and will go into operation in 2007. Commercial plants are already in operation overseas[5]. Several plans to build commercial plants combining with CO_2 storage are being developed[6].

IGFC is a triple-combined power generation system combining IGCC and high-temperature fuel cells. Table 1 shows the characteristics of IGFC in comparison with conventional coal-fired and IGCC power generation[7]. One of the reasons why IGFC is called the "ultimate coal-based power generation technology" is that the power generation efficiency of IGFC reaches 50 to 55%, far exceeding that of pulverized coal-fired and IGCC power generation.

Figure 3 summarizes clean coal technology focused on IGFC. It not only allows high-efficiency power generation but also has the following characteristics.

- A wide variety of coals can be used, allowing the effective use of coal: Low-grade coals with high moisture content and low calorific values, such as brown and subbituminous coals, are difficult to use in conventional pulverized coal-fired power generation,

Table 1 : Comparison of coal-fired power generation technologies

Technology	Configuration	Power Generation method	Power Generation efficiency (HHV, net)	Applicable Coal type
Conventional coal-fired plant (pulverized coal-fired)		Steam turbine	42-43%	Bituminous coal
IGCC		Gas turbine Steam turbine	46-48%	Bituminous coal Low-grade coal
IGFC		High-temperature fuel cells Gas turbine Steam turbine	50-55%	Bituminous coal Low-grade coal

Prepared by the STFC based on Reference[7] but can be used as fuel for IGCC or IGFC power generation through the relatively easy gasification process.

- Environmental pollutants and CO_2 can be easily removed and captured: Environmental pollutants can be easily removed by placing a gas clean-up unit downstream the gasification process. High CO_2 concentrations in the exhaust gas allow CO_2 capture by a CO_2 capture unit at relatively low cost. Near-zero emissions can be achieved by transporting the captured CO_2 by pipelines or tankers, and by sequestrating and storing it underground or in the ocean.

Figure 4 shows the CO_2 emission intensity of each power generation system. Of the coal-based systems, IGFC has a combination of CO_2 capture and sequestration (CCS) technology, which has the lowest CO_2 emission rate[8,9].

The areas of clean coal technology focused on IGFC include high-temperature fuel cells as a key technology, as well as coal gasification and gas clean-up technology CO_2 separation technology and CCS technology. Figure 5 shows change in the number of science and technology papers published in the world to explain research and development trends in each clean coal technology area. In the 1980s, most research focused on coal liquefaction technology. This reflects the fact that due to the two oil shocks in the 1970s, coal was mainly seen as the alternative to oil. In the 1990s and beyond, research focused on coal gasification technology and high-temperature fuel cell (molten carbonate fuel cells; MCFC and solid oxide fuel cells; SOFC) technology because

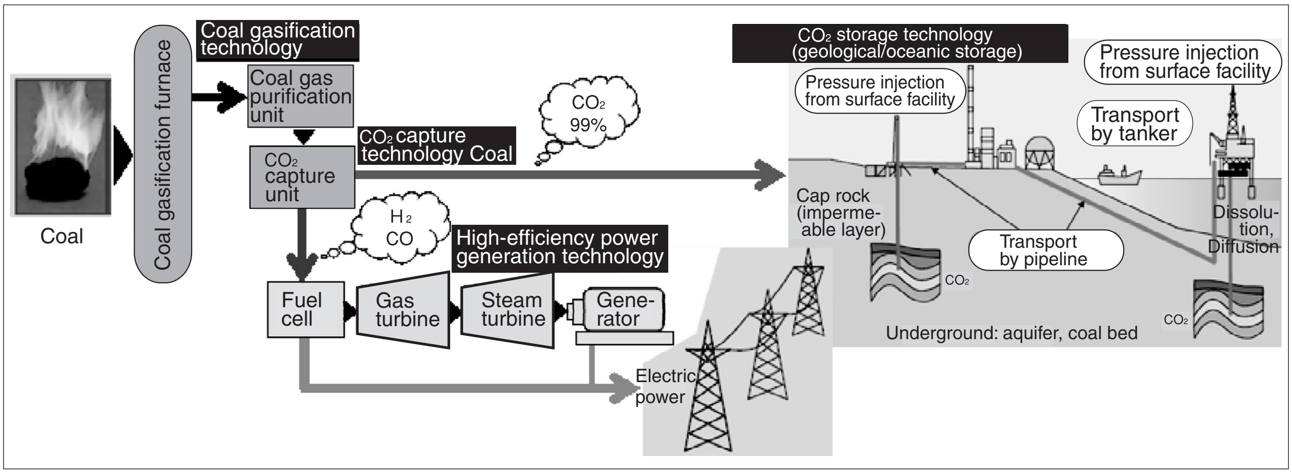


Figure 3 : Overview of clean coal technology adopting IGFC

Prepared by the STFC based on Reference[2]

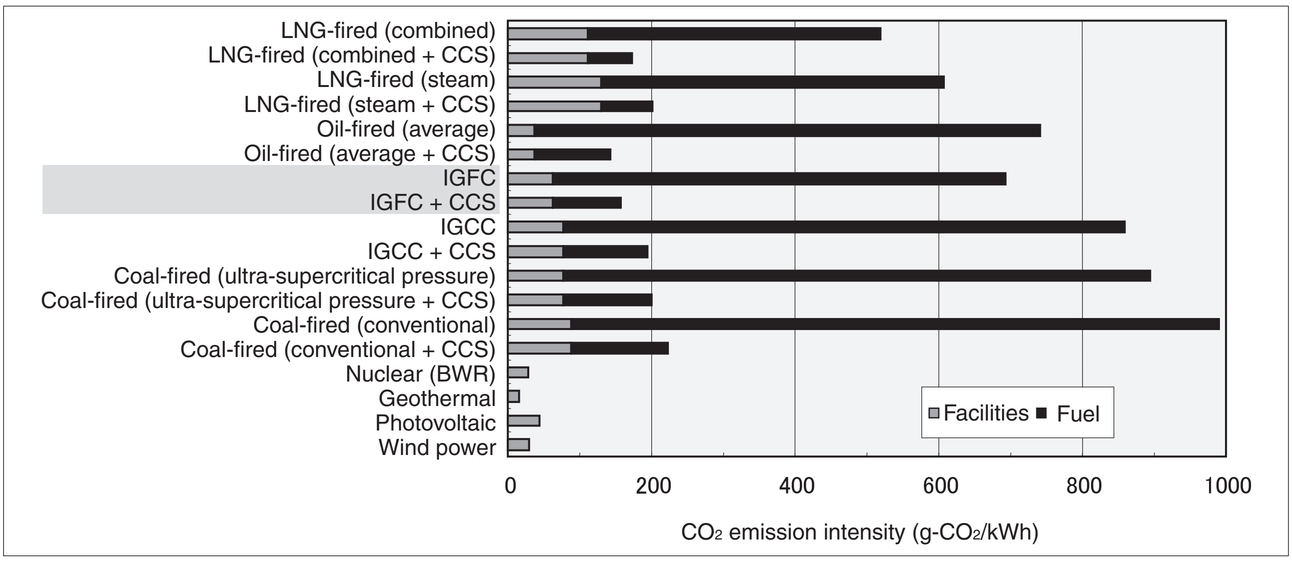


Figure 4 : Comparison of CO_2 emission intensity among power generation systems

Prepared by the STFC based on the References[4,8,9]

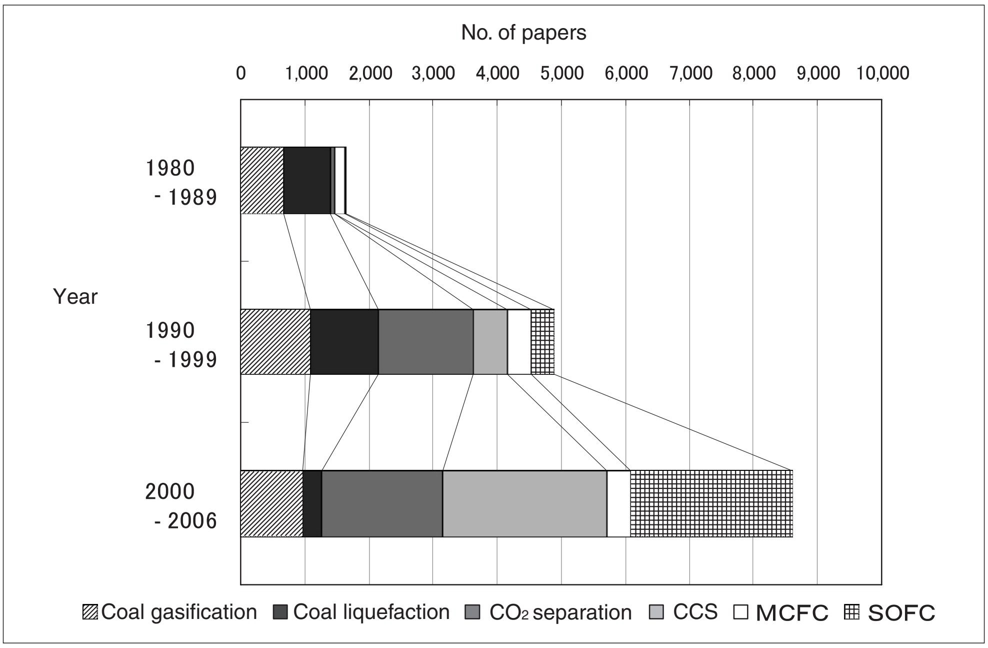


Figure 5 : Change in the number of science and technology papers published in the world in the area of clean coal technology

repared by the STFC based on data from Thomson's "Web of Science"

global warming problems surfaced in the 1990s. Now, research is increasingly focused on CCS technology aimed at zero emissions.

3 Status of research and development of IGFC

3-1 Status of development of high-temperature fuel cells[10]

The key technology for IGFC, the ultimate coal-based power generation system, is fuel cells that achieve high-efficiency power generation. Fuel cells are divided into two types: high-temperature and low-temperature fuel cells. The high-temperature type is suitable for IGFC for the following reasons:

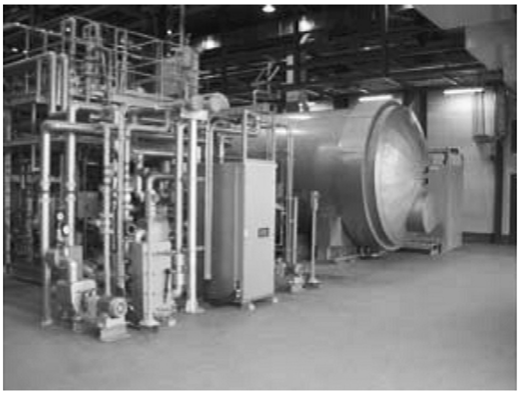
(i) Due to high-temperature operation, the electrode reaction of hydrogen and carbon monoxide, primary components of coal gas, proceeds in high rate and coal gas can be used directly. In low-temperature fuel cells, due to low temperature operation, the electrode reaction rate is relatively slowand an expensive platinum catalyst is required to increase the rate. Carbon monoxide in coal gas may cause adsorption poisoning to the platinum catalyst and a carbon monoxide removal unit is also required, adding to the complexity of the system.

(ii) A system can be easily converted into a combined cycle of gas and steam turbines using high-temperature exhaust gas, allowing a dramatic improvement in the overall power generation efficiency of the system.

There are two types of high-temperature fuel cells: molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC). The operating temperature is about 600 to 670°C for MCFC and about 750 to 1,000°C for SOFC. A combined cycle using high-temperature exhaust gas can be implemented. Currently, both MCFC and SOFC are being developed in parallel. The status of development of both types is described in the following sections.

(1) Molten carbonate fuel cells (MCFC)

In Japan, a study on MCFC began in the early 1980s as a national project, and a 1 MW-class plant was developed. The results of the study developed into a 300 kW-class, city gas-based fuel cell system for distributed power generation. Two fuel cell units were operated for demonstration purposes during the Aichi Expo and achieved a maximum power generation efficiency of 51%



MCFC (300 kW-class)

SOFC (125 kW-class)

Figure 6 : External view of the high-temperature fuel cell systems

Source: References[10,13]

(LHV, gross). These units were moved to Chubu Rinku Town (Tokoname City) in FY 2006 and have been in operation since then (Figure 6)[11].

Outside Japan, a US company and a German company developed a 250 kW-class, ambient pressure system through a cross license agreement and achieved a power generation efficiency of about 47% (LHV, net). More than 50 units have been shipped worldwide, some of which exceeded a total operation time of 25,000 hours. The system can supply both electricity and heat and is used in a variety of areas such as sewage treatment plants (using sludge digestion gas), manufacturing plants (using natural gas, city gas or coal-mine methane gas), hotels, hospitals, universities and for electricity quality improvement[12].

In Japan, a natural gas-based, large 1 MW-class pressurized plant expected to be used for electric utilities was operated in 1999 by the New Energy and Industrial Technology Development Organization (NEDO). In the US, a city gas-based, 2 MW ambient pressure plant was operated in 1997, and a 1 MW-class plant using digestion gas from a sewage treatment plant was developed in 2004[10].

In Japan, the feasibility of applying coal gas to IGFC was evaluated using 10 kW-class stacks, and the stability of the performance of the stacks was confirmed. Also, damage from coal gas impurities to MCFC stack components was evaluated in detail. The effect of impurity concentrations of ppm order on the cell voltage and the degradation mechanism were investigated. Also, the allowable impurity concentration was identified.

(2) Solid oxide fuel cells (SOFC)

A 10 kW-class module was developed by 2004 as a national SOFC project of Japan. Subsequently, modules for cogeneration (10 to 20 kW-class) and combined-cycle (200 kW-class) applications were developed in the system technology development program (FY 2004 to 2007) focusing on introduction into the market for small to medium distributed power generation systems using city gas and oil-based fuel. Attempts to use SOFC as a small power supply are being pursued. There is a plan to demonstrate the performance of 1 to 5 kW-class systems for residential applications.

Larger SOFC systems are being actively developed in the US. A 100 kW-class ambient pressure system has been operated for demonstration purposes since 1997 by changing the installation location from the Netherlands to Germany to Italy. The power generation efficiency of the system is 46% (LHV, net). A 200 kW-class pressurized hybrid system was developed over the period from 2000 to 2003 and operated for 3,300 hours. The power generation efficiency was 53% (LHV, DC gross). Currently, the US company is focusing on the development of an ambient pressure, 125 kW-class system (Figure 6)[13]. Rolls-Royce of the UK is also developing SOFC systems with the goal of developing a 1 MW-class system. In 2005, they generated power of up to 60 kW-class[8]. Table 2 summarizes the results and current activities of the development of MCFC and SOFC systems.

Table 2 : Results and current activities of development of high-temperature fuel cells

	Japan		Overseas (US)	
	MCFC	SOFC	MCFC	SOFC
Demonstrated capacity	150 to 1,000 kW	1 to 40 kW	250 to 2,000 kW	5 to 200 kW
Demonstrated efficiency (HHV)	41% (net, 300 kW system*)	41% (net, 1 kW-class system)	43% (net, 250 kW system)	47% (based on stack DC + MGT AC*)
Demonstrated life	5,000h (1 MW system) 12,000h (10 kW stack) 50,000h (cell, pressurized)	7,000 h (10 kW stack)	Over 25,000 h (250 kW system)	16,600 h (100 kW system, stacks replaced) 70,000 h (cell, ambient pressure)
Current expected applications	Electric power utilities (natural gas)	Distributed power supply (city gas)	Distributed power supply (city gas)	Distributed power supply (city gas) Power supply for military, communications applications
Issues in application to IGFC	• Capacity enlargement, cost reduction	• Investigation of effect of impurities • Extending life • Systematization • Capacity enlargement, cost reduction	• Review of systems suitable for IGFC (pressurization, external reforming) • Capacity enlargement, cost reduction	• Investigation of effect of impurities • Extending life • Systematization • Capacity enlargement, cost reduction

* indicates a reference value (corrected by calculation)

Prepared by the STFC based on Reference[10]

3-2 Comparison of relevant research and development projects of various countries

(1) FutureGen and SECA Projects of the US

In the US, the FutureGen Project of the Department of Energy (DOE) aimed at zero CO_2 emission coal gasification power plants is underway. In February 2003, President Bush stated that a total of one billion US dollars will be invested in the FutureGen Project over a 10-year period[14]. The project aims at demonstrating coal gas-fired power generation systems that produce hydrogen as well as CCS. The US is leading the world in the development of coal gasification technology. Commercial IGCC technology has already been achieved mainly by oil majors. High-temperature fuel cells have been developed since 2000 in the Solid State Energy Conversion Alliance (SECA) Project[15] as part of the FutureGen Project under the leadership of DOE's National Energy Technology Laboratory (NETL). The goals of the SECA Project are to develop 3 to 10 kW core modules by 2010 that can be used for a variety of applications such as stationary, portable and military applications, and to significantly reduce cost (400 US$/kW). Six corporate teams are participating in the SECA Project and each of them is developing characteristic SOFC applications separately. Each corporate team is supported by national laboratories, universities and other research organizations. The results of the SECA Project will be incorporated into coal gasification power generation plants developed by the FutureGen Project in 2010 and afterwards.

The Environmental Protection Agency (EPA) and DOE conducted a detailed cost assessment of coal gasification power generation and CO_2 collection and storage, and estimated the cost of CO_2 collection at US$ 24 per CO_2-t[16].

(2) COAL21 Program of Australia

Australia is the world's number-one exporter of coal. Federal and state governments, the coal and electricity industries formed a partnership to achieve clean coal technology that allows both energy security and environmental compatibility, and announced a program called COAL21 in March 2004[17]. Australia leads the Carbon Sequestration Leadership Forum (CSLF) by making use of its abundant potential for geological storage of CO_2. It initiated projects to assess geological CO_2 storage with China and India, based on the outcomes of the CSLF. However, research and development activities on high-temperature fuel cells are not being actively pursued.

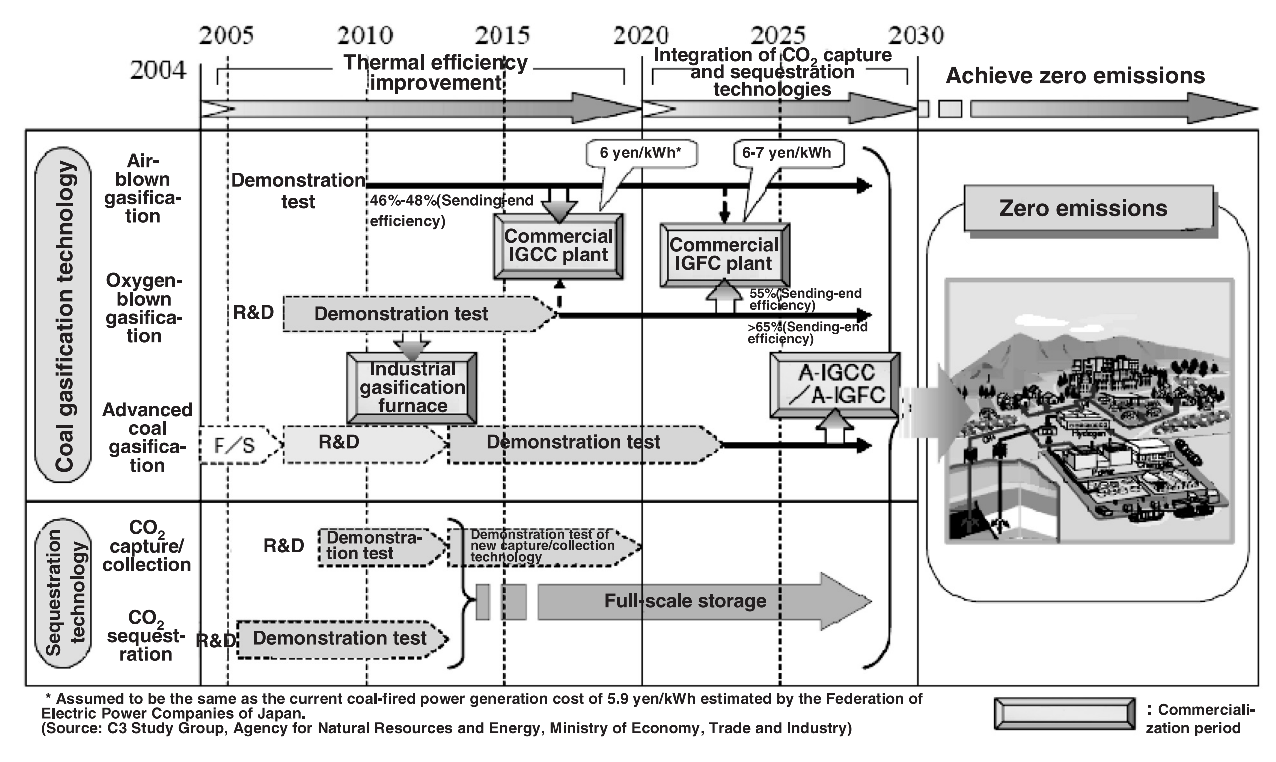


Figure 7 : Road map for clean coal technology

Source: Reference[22]

(3) GreenGen Project of China

Ninety-five percent of China's electricity industry depends on coal-fired power generation, and there is a strong social demand for clean coal technology. China had been conducting research and development on coal gasification technology since the late 1990s and developed a proprietary two-stage jet bed gasification process based on US technology[18,19]. In 2004, it initiated a national project called GreenGen aimed at demonstrating an IGFC power generation system integrated with CCS. In 2005, China HuaNeng Group announced its participation in the US FutureGen Project. China is looking into the proprietary development of clean coal technology, and it positioned the technology as a priority research topic in the "National medium- and long-term program for science and technology development" announced in February 2006. In China, basic research on high-temperature fuel cells has just begun.

(4) Development projects in Japan

In 1995, NEDO and Electric Power Development Co., Ltd jointly initiated the Coal Energy Application for Gas, Liquid & Electricity (EAGLE) project aiming to achieve Japan's proprietary coal gasification technology applicable to IGFC. In 2002, a coal gasification pilot plant began demonstration operation and produced satisfactory results as planned. A system to purify coal gas into components applicable to high-temperature fuel cells has already been achieved. In FY 2006, the final year of the project, as a step toward the review stage, the demonstration of scale-up technology was conducted and the coal type used in the test was expanded to include US, Australian, Chinese and Indonesian coals. The design of a commercialization plant with a coal processing capacity of 1000 t/day (150,000 kW IGCC equivalent) will begin next year[20]. A demonstration test on a combination of a coal gasification unit and a CO_2 capture and collection unit will begin in 2007. However, there is no concrete road map for achieving IGFC by combining these units and high-temperature fuel cells.

In the area of geological CO_2 storage, a demonstration test is underway at the Research Institute of Innovative Technology for the Earth[21]. However, there is no specific plan for a demonstration test on a combination with a coal-fired power plant.

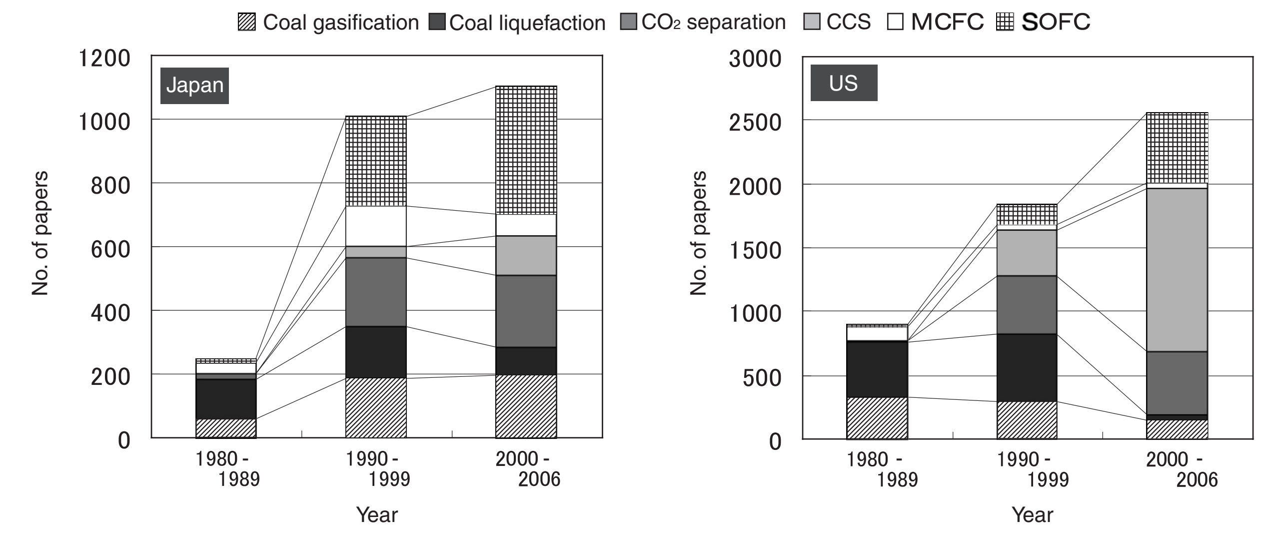


Figure 8 : Change in the share of science and technology papers in the area of clean coal technology produced in Japan and the US

Prepared by the STFC based on data from Thomson's "Web of Science"

The Agency for Natural Resources and Energy developed a road map for achieving a zero-emission society by 2030 (Figure 7)[22]. However, there is no specific plan for demonstrating the system as a whole, although relevant element technologies are being developed in individual projects. As described in (1) to (3) above, this contrasts with the US, Australia and China, which have specific timelines for the overall demonstration test of clean coal technology integrating coal gasification power plants and CCS.

3-3 Issues in achieving IGFC in Japan

(1) Defining the positioning of the technology as a means of reducing CO_2 emissions

The future of clean coal technology as a whole, including CCS, needs to be clearly pictured to show that IGFC is an effective means of reducing CO_2 emissions in combating global warming. This requires progress in research and demonstration, particularly academic research, on CCS technology[23].

As mentioned earlier, in the US, the positioning of IGCC and IGFC as a means of reducing CO_2 emissions is defined, and a specific master plan for clean coal technology integrating IGCC (IGFC) power plants and CCS has been developed and is being implemented.

The number of science and technology papers on clean coal technology produced in Japan and the US is compared to identify the factors contributing to the difference between the two countries. The data for the 1980s and beyond show that clean coal technology accounts for the largest share (34%) with 5,283 papers in the US while it accounts for the second largest share (15%) with 2357papers in Japan. Thus, Japan is comparable to the US in this area. However, the change in the number of science and technology papers on individual element technologies shows a significant difference in the trend between the two countries (Figure 8).

The trend for the US shows that research had been actively pursued in the areas of coal gasification and coal liquefaction, and in recent years, the focus of research has shifted to CO_2 separation and CCS. Particularly in the area of CCS technology, the US has produced 50% of the research papers published worldwide, significantly leading other countries. Progress in research on CCS is probably a significant contributing factor to the fact that in the US, clean coal technology, including IGFC, is recognized as an effective means of reducing CO_2.

In the areas of coal liquefaction, coal gasification, high-temperature fuel cell and CO_2 separation technologies, Japan is comparable to or better than the US, but is far behind the US in the area of CCS. There has been no adequate discussion of the positioning of clean coal technology, including IGFC, as a means of reducing CO_2 probably because there has been no progress in academic research on CCS technology

Table 3 : Issues in realizing IGFC

	Issue	Description
Coal gasifier	Optimal design of gasification process	When air is used as an oxidant for coal gasification, the fuel cell pressure loss increases due to nitrogen, resulting in potential gas leaks; redesign the fuel cell operating pressure and related gasification pressure, as well as the gas flow channel in the fuel cells and the overall system configuration.
	Identification of improvements to gasification unit for IGCC	Redesign the system so that the maximum performance of fuel cells can be achieved, and improve the gasification unit so that its performance matches the improved performance of the system.
	Optimal system design by adding CO_2 capture capability	Redesign and improve the system as a result of adding a CO_2 capture unit.
Gas clean-up unit	Establishment of an advanced gas clean-up process	Develop an advanced gas clean-up process to achieve the allowable fuel cell level.
Fuel cells	Investigation of allowable concentrations of coal gas impurities	Investigate the effect of sulfur, halogen and nitrogen compounds of ppm order on the function of the Ni catalyst; investigate impurity-resistance levels.
	Selection of the appropriate fuel cell type	Select either MCFC or SOFC by comparison, including the reforming process (internal/external), at the appropriate time point.
	Investigation of methanation when coal gas is used	Review the fuel cell configuration and operating conditions due to methane formation from CO and H_2, primary coal gas components, and their exothermic reaction.

Prepared by the STFC

which is a key technology for IGFC.

The lack of progress in research on CCS in Japan is due to the fact that although CCS technology requires expertise and knowledge of resource exploration and geology, both academia and industries lack it. The US has many natural resource majors and basic research centers that have abundant know-how in these areas, but Japan has few. In order to develop CCS technology in Japan, it is necessary to enhance these areas or promote cooperation with leading overseas research centers in these areas. Either case requires support from the government.

In Japan, where the economy as a whole is growing slowly, the market for the commercial power generation equipment is saturated and the motivation for electric power companies to invest in new equipment is declining. The recent deregulation of the domestic electricity market has accelerated this trend. Unless the positioning of IGFC as a means of reducing CO_2 is defined, electric power companies as the users of IGFC systems will not be motivated to introduce the systems. Consequently, high-temperature fuel cell manufactures will prioritize the development of medium-capacity fuel cells for distributed power generation for which demand is expected from customers other than electric power companies, becoming less motivated to invest in the research and development of IGFC.

It is necessary to focus academic research on CCS, including cooperation with overseas research organizations, in order to break this vicious cycle, define the social importance of clean coal technology including IGFC, and consequently to develop a master plan.

(2) Identifying issues and milestones in applying high-temperature fuel cells to IGFC

Progress in high-temperature fuel cells and other technology areas such as coal gasification, gas clean-up and CO_2 separation technologies, as well as coordination among concerned parties, is necessary to achieve IGFC. In Japan, coal gasification and CCS technologies are now in the demonstration stage for IGCC, ahead of high-temperature fuel cells for IGFC still in the technical development stage. Disagreement at the stage of research and development, such as this, is inevitable. However, it contributes to impeding communication and collaboration among concerned parties.

There are still high technological hurdles for the practical application of high-temperature fuel cells. In Japan, particularly in the area of MCFC, issues in the stage of basic research on fuel cells for IGFC, such as durability on the bench scale, investigation of the effect of coal gas impurities and establishment of an optimal hydrogen production process, have been cleared. Table 3 summarizes expected technological issues of high-temperature fuel cells in achieving

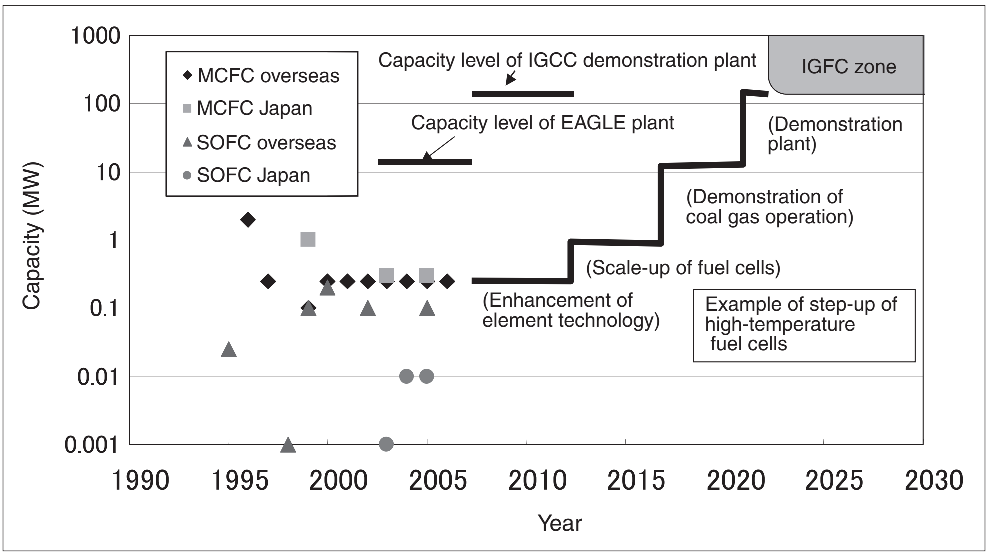


Figure 9 : Example of milestones for achieving a pilot plant scale

Prepared by the STFC

a pilot IGFC plant as the next step. In order to deepen discussion about the master plan among those involved in clean coal technology, those involved in the research and development of high-temperature fuel cells need to take the initiative in defining concrete measures and development steps to overcome the issues shown in Table 3, and developing milestones with gate goals defined to move toward subsequent steps (Figure 9).

MCFC and SOFC for IGFC have been developed independently of each other, and a difference has occurred in the progress of development. For SOFC in particular, there has been little study on the use of coal gas, and many unknowns remain regarding the degradation mechanism and allowable concentrations. It may be necessary to go back to the stage of material development in some cases. These issues have been cleared for MCFC. Therefore, at the moment, MCFC is closer to achieving IGFC. A comprehensive discussion is required to determine when and how to select the type of high-temperature fuel cells for IGFC, taking into account the progress in the basic research and development stage.

A specific plan for developing a system integrating coal gasification technology and fuel cells needs to be developed as soon as possible, taking into account the progress of coal gasification technology, which has already been established for IGCC, and the time of completion of development of large-capacity fuel cells. The plan guides and accelerates practical applications of IGFC.

IGFC is a technology that takes time to develop. Long-term support in developing the technology can be made available only by setting development steps in accordance with progress in the development of coal gasification technology and fuel cells.

(3) Further progress in the development of relevant key technologies

Progress in the development of high-temperature fuel cells as well as a variety of peripheral technologies is essential to achieve IGFC. Also, further improvement in efficiency is required of coal gasification technology. In Japan, coal gasification technology is being developed ahead of IGFC, as part of the development of IGCC. Results from this development can be utilized for the development of IGFC. In particular, the two-stage spiral flow gasifier being developed under the EAGLE project has the advantage that it can burn a variety of coals, compared to the foreign technologies.

Exergy(available energy)-recovery gasification technology, an advanced, next-generation coal gasification technology, has been invented. In Advanced IGFC (A-IGFC) which incorporates the technology, coal is gasified at low temperatures (700 to 900°C) and the exhaust gas from the high-temperature gas turbines and fuel cells is used as heat for gasification, resulting in an

	Conventional IGCC/IGFC	A-IGCC/IGFC
Combined system	Cascading type	Exergy-recovery type
Gasification system	Partial high-temperature oxidation (1,100-1,500°C)	Steam reform (700-1,000°C)
Gasification furnace	Jet bed	High-density high-speed circulating fluid bed (multi-loop high density CFB)
Power generation efficiency (HHV.net)	46-48% / 55%	53-57% / 65%

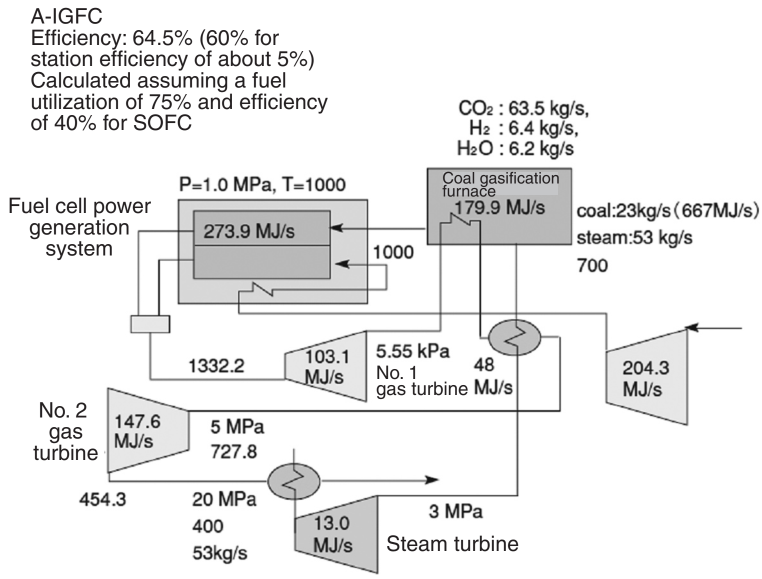


Figure 10 : Configuration and characteristics of Advanced IGFC (A-IGFC)

Source: Reference[25]

estimated power generation efficiency of as high as 70% (Figure 10)[24,25]. Basic research in this area will begin in FY 2007 under the leadership of the University of Tokyo. It requires research based on expertise and knowledge accumulated in disciplines as diverse as mechanical engineering, materials engineering, computer science and combustion engineering.

(4) Feasibility study of international cooperation

It is important to deepen collaboration with China and other major coal-importing countries and promote international cooperation in developing IGFC technology, based on technologies accumulated in the area of clean coal technology over the past years in Japan. In Asian countries, mainly China and India, dependence on coal is expected to increase with their rapidly growing economies. Clean coal technology, including IGFC, is a vital technology from the perspective of energy security and environmental protection. The introduction of the technology into other coal-importing countries in Asia is desirable to Japan, as an Asian country, and in terms of energy demand and supply and global environmental issues. These Asian countries where rapid development of infrastructures for coal-fired power generation is expected will be better markets than Japan for clean coal technology developed in Japan.

Since clean coal technology is still at the stage of research and development, an intellectual property protection and distribution program needs to be established by countries participating in the international cooperation in order to develop smooth cooperative relationships. First, we need to clarify what cooperation we can offer and in which stages of development we can offer cooperation. Then, we need comprehensive discussion, including technical and institutional issues, with Asian countries that will need clean coal technology in the future.

In the Asia-Pacific Partnership on Clean Development and Climate (APP CDC) with six participating members of the US as the organizer, Japan, Korea, Australia, China and India, a task force on clean coal technology has been established with the aim of establishing a technology development program by the next ministerial meeting in 2007 and promoting CCS[26]. It is necessary to contribute towards intensifying international activities such as APP CDC.

4 Conclusion

The integrated coal gasification fuel cell combined cycle (IGFC) is the most efficient coal-fired power generation technology and contributes to reducing CO_2 emissions. It should be vigorously pursued to respond to sharp oil price hikes, such as those that have occurred recently, to meet the expected increase in energy demand in developing countries and to ensure the energy security of Japan as well as global environmental protection. However, there is no comprehensive road map in Japan for developing systems integrating individual element technologies for clean coal technology. There is no specific demonstration plan, either.

Our suggestions for the early achievement of IGFC are described below.

(1) Defining the positioning of the technology as a means of reducing CO_2 emissions

The future of clean coal technology as a whole, including CCS needs to be clearly pictured in order to show that IGFC is an effective means of reducing CO_2 emissions in combating global warming. This requires progress in academic research on CCS technology, which is inadequate in Japan. In the US, as the progress on CCS technology, the positioning of clean coal technology and IGFC as a means of reducing CO_2 is accepted by society. Also, a specific master plan for clean coal technology integrating IGCC (IGFC) power plants and CCS has been developed and is being implemented in a top-down manner. Japan needs our own specific master plan. The positioning of IGFC should be defined in the plan. In order for clean coal technology, including IGFC, to be socially accepted in Japan as a means of reducing CO_2, academic research on CCS, in which Japan lags behind, must be accelerated.

(2) Identifying issues and milestones in applying high-temperature fuel cells to IGFC

Progress in high-temperature fuel cells and other technology areas such as coal gasification, gas purification and CCS technologies, as well as collaboration among concerned parties, is necessary to achieve IGFC. At the moment, coal gasification and CO_2 separation technologies are in the demonstration stage for IGCC, ahead of high-temperature fuel cells for IGFC. Disagreement at the stage of research and development, such as this, is inevitable. However, it contributes to impeding communication and collaboration among concerned parties. Some issues in the stage of basic research on high-temperature fuel cells for IGFC, such as durability on the bench scale and investigation of the effect of coal gas impurities have been cleared. In order to deepen discussion about the master plan among those involved in clean coal technology and achieve a pilot IGFC plant as the next step, those involved in research and development of high-temperature fuel cells need to take the initiative in identifying technological issues, defining concrete measures and development steps to overcome the issues, and developing milestones with gate goals defined to move toward subsequent steps.

(3) Further progress in the development of relevant key technologies

Progress in the development of high-temperature fuel cells as well as a variety of peripheral technologies is essential to achieve IGFC. Coal gasification technology is a key technology that affects overall power generation efficiency, and therefore, research and development for further improvement in the efficiency is required. Progress in this area requires research based on expertise and knowledge accumulated in disciplines as diverse as mechanical engineering, materials engineering, computer science and combustion engineering.

(4) Feasibility study of international ooperation

It is important to enhance collaboration with large potential coal-importing countries, especially in Asia, and promote international cooperation in IGFC technology. Clean coal technology, including IGFC, is in the stage of research and development. An intellectual property protection and distribution program needs to be established by countries participating in the international cooperation in order to develop smooth cooperative relationships. First, we need to clarify what cooperation we can offer and in which stages of development we can offer cooperation. Then, we need comprehensive discussion, including technical and institutional issues, with participating countries.

Acknowledgements

We received valuable comments, advice and materials on overall issues from Associate Professor Atsushi Tsutsumi, University of Tokyo; Associate Professor Tetsuya Suekane, Tokyo Institute of Technology; and the Coal Division of the Natural Resources and Fuel Department, Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry. Also, we received valuable information and materials from Mr. Shunichi Yanai, Senior Researcher, and Mr. Kyoichi Kogami, Project Coordinator, Environment Technology Development Department of the New Energy and Industrial Technology Development Organization (NEDO); Mr. Takashi Ujiie, Senior Researcher, Fuel Cell and Hydrogen Technology Development Department of NEDO; Mr. Yasuo Arai, Manager, Mr. Yoshiaki Sakai, Deputy Manager, Planning and Coordination Department of the Japan Coal Energy Center (JCOAL); Mr. Akemitsu Akimoto, Manager, Research and Development Department of JCOAL; Mr. Takashi Ohsumi, Senior Researcher, Research Institute of Innovative Technology for the Earth; and Mr. Hiroyuki Sakata, Deputy Section Manager, Clean Coal Power R&D Co., Ltd. We would like to express our sincere appreciation to those mentioned above.

References

[1] The Institute of Energy Economics, Japan, “Demand and Supply, Price Trends and Future Utilization of Coal,” January 2006. (Japanese)

[2] The Institute of Energy Economics, Japan, “Asia/World Energy Outlook 2006,” October 2006. (Japanese)

[3] Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry, “New National Energy Strategy,” May 2006. (Japanese)

[4] IPCC, “Special Report on Carbon Dioxide Capture and Storage,” September 2006.

[5] Arai, “Trends in Commercialization of Coal Gasification in the US,” JCOAL Journal, Vol. 4, March 2006, p 7 (Japanese): http://www.jcoal.or.jp/publication/jcoaljournal/dlfiles/JCOAL_Journal-3.pdf

[6] Harry Audus, “An Update on CCS: Recent Developments,” 2nd IEA Workshop on Legal Aspects of Storing CO_2, October 17, 2006. http://www.iea.org/Textbase/work/2006/carbon/4.pdf

[7] CRIEPI Review No. 44, “Toward the Realization of Integrated Coal Gasification Combined Cycle,” October 2001. (Japanese)

[8] Hondo et al., “Evaluation of Power Generation Technologies based on Life Cycle CO_2 Emissions - Re-estimation using Latest Data and Effect of Difference in Assumption,” CRIEPI Annual Research Reports, Y99009, 2000. (Japanese)

[9] Yoji Uchiyama, “Our Energy: Present and Future,” Baifukan Co., Ltd., 1996. (Japanese)

[10] CRIEPI Review No. 51, “Fuel Cell Power Generation Technology,” March 2004. (Japanese)

[11] New Energy and Industrial Technology Development Organization (NEDO), “A booklet for Expo 2005 Aichi, Japan” (Japanese) http://www.nedo.go.jp/expo2005/file/for_general_j.pdf

[12] FuelCell Energy’s homepage : http://www.fce.com/

[13] Lucerne Fuel Cell Forum Abstracts 2006

[14] Victor Der, “FutureGen - “Zero Emission” Energy from Coal,” Proceedings from Advanced Clean Coal Technology International Symposium 2006, Japan Coal Energy Center, September 5, 2006. http://www.jcoal.or.jp/publication/kokusaikaigi/pdf/CCD2006/CCD2006SymposiumB.pdf

[15] http://www.netl.doe.gov/technologies/coalpower/distgen/seca/

[16] US EPA, “Environmental Footprints and Costs of Coal-Based IGCC and Pulverized

Coal Technologies," July 2006.
http://www.epa.gov/airmarkets/articles/IGCCreport.pdf

[17] John Karas, "Low Emission Technology for Coal: The Australian Contribution," Proceedings from Advanced Clean Coal Technology International Symposium 2006, Japan Coal Energy Center, September 5, 2006.
http://www.jcoal.or.jp/publication/kokusaikaigi/pdf/CCD2006/CCD2006SymposiumE.pdf

[18] Kawamura, "Trends in Coal Gasification Operations in China," JIE Journal, Vol. 85, No. 3, March 2006, p 179. (Japanese)

[19] Gao Shinwang, "Near Zero Emission Coal-Based Power Generation in China - GreenGen Project," Proceedings from Advanced Clean Coal Technology International Symposium 2006, Japan Coal Energy Center, September 5, 2006.
http://www.jcoal.or.jp/publication/kokusaikaigi/pdf/CCD2006/CCD2006SymposiumF.pdf

[20] Suzuki, "The Status of the EAGLE Project," Proceedings from Advanced Clean Coal Technology International Symposium 2006, Japan Coal Energy Center, September 5, 2006. : http://www.jcoal.or.jp/publication/kokusaikaigi/pdf/CCD2006/CCD2006SymposiumC.pdf

[21] RITE CO_2 Geological Sequestration Project Homepage: http://www.rite.or.jp/Japanese/project/tityu/tityu.html

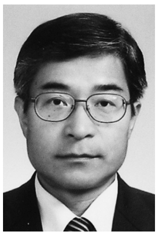
[22] Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry, Interim Report of the Clean Coal Cycle (C3) Study Group "Japan's New Coal Policy Towards 2030," June 2004.

[23] OECD/IEA, "Discussion Paper for 2nd IEA/CSLF Workshop on Legal Aspects of Carbon Capture and Storage," October 17, 2006. http://www.iea.org/Textbase/work/2006/carbon/2.pdf

[24] NEDO, JCOAL, "Clean Coal Technology in Japan" http://www.jcoal.or.jp/cctinjapan/cctinjapan.html

[25] Tsutsumi, "Advanced IGCC/IGFC Using Exergy Recuperation Technology," CCT Journal, No. 11, August 2004.
http://www.brain-c-jcoal.info/publication-files/oldccuj/cct-journal/CCT_Journal-11.pdf

[26] Ministry of Economy, Trade and Industry, "First ministerial meeting of the Asia-Pacific Partnership on Clean Development and Climate," January 12, 2006.
http://www.meti.go.jp/press/20060112003/app-set.pdf



Takao WATANABE, PhD
Affiliated Fellow, NISTEP
Energy Engineering Research Laboratory, Central Research Institute of Electric Power Industry
http://criepi.denken.or.jp/jp/index.html

Doctor of Engineering. Engaged in development of performance evaluation technology, high-performance technology and system technology of fuel cells; areas of specialty include electrical engineering and electrochemistry; currently engaged in technology development in the areas of energy and the environment with a focus on fuel cells.

Seiji MAEDA, PhD
Environment and Energy Research Unit

Doctor of Engineering. Engaged in the development of energy storage and conversion systems and project development at a private company; areas of specialty include electrochemistry and materials engineering; current interests include science and technology policies in the areas of energy and the environment, and innovation management.

(Original Japanese version: published in November 2006)